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Summary of Labyrinths and Penetrations in the Muon Test Area (MTA) Enclosure

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1 Introduction

The MuCOOL Test Area (MTA), an experimental enclosure situated southwest of Linac and west of Booster, is served by the MuCOOL beamline. Linac beam is kicked westwards and transported through a 12-foot-thick shield wall into the MTA enclosure.

To conduct studies of Linac beam properties such as emittance, 400 MeV negative hydrogen ions are transported through the shield wall and into a movable emittance absorber in MTA.

To provide beam to experiments, the emittance absorber is moved out of the beamline, and beam continues into experimental apparatus further downstream.

A rate-limiting device inhibits the operation of the C-magnet to control the rate at which pulses are sent into the MuCOOL beamline.

For accident conditions, doses from numerous penetrations must be analyzed to assess operation of this beamline. We generally presume that an accident can lose beam along the beamline, anywhere in the enclosure, at maximum intensity, for one hour.

Doses arising from normal operation of the beamline are also of interest. In normal operation, beam is intentionally deposited on targets, collimators, or absorbers at the maximum pulse rate permitted.

Two methods were used to obtain dose rates. First, labyrinth dose rate calculations employed an approved spreadsheet methodology, used in previous Fermilab shielding assessments. Second, some penetrations were analyzed with MARS shielding code simulations.

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2 Beam Parameters Used in Calculations

Our strategy is first to calculate, as a baseline, the dose at each penetration due to losses at maximum approved Linac beam power.

Then, for operational scenarios, such "base" doses are scaled to determine doses for other combinations of beam parameters. In particular, this will be done for the two modes considered in the MuCOOL Shielding Assessment [Reference 1], namely the Emittance Mode and the Experiment Mode.

2.1 Base Dose at Linac Approved Operating Intensity

Labyrinth calculations used an intensity of 1.6E13 protons per pulse, at an energy of 400 MeV. The hourly pulse rate considered is 22125 pulses per hour, which would yield at this intensity 3.54E17 protons per hour.

MARS calculations, performed by Igor Rakhno for some of the MTA penetrations [2], also assumed a beam intensity of 1.6E13 protons per pulse.

We will review the dose estimated for each of the penetrations under these very intense beam conditions.

In general, the worst-case loss location and condition were determined for each individual labyrinth and penetration geometry, producing the largest prompt dose per pulse achievable at their respective exit.

2.2 Determining Doses for MuCOOL Shielding Assessment Conditions

The MuCOOL shielding assessment [1] considers beam delivered at much lower repetition rates. The hourly doses described above are scaled and presented in Section 4, entitled "2010 Shielding Assessment Beam Conditions," below. Results for two sets of operating conditions, Emittance Mode and Experiment Mode, are discussed there

In Emittance Mode, 400 MeV beam is deposited on the emittance absorber at 1.6E13 protons per pulse and up to 600 pulses per hour.

In Experiment Mode, 400 MeV beam is deposited on an arbitrary device, at an arbitrary location along the beamline, at 1.6E13 protons per pulse and up to 60 pulses per hour. It is beyond the scope of this document to provide analysis of any individual experiment; specific details must be analyzed on a case-by-case

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basis in separate documents.

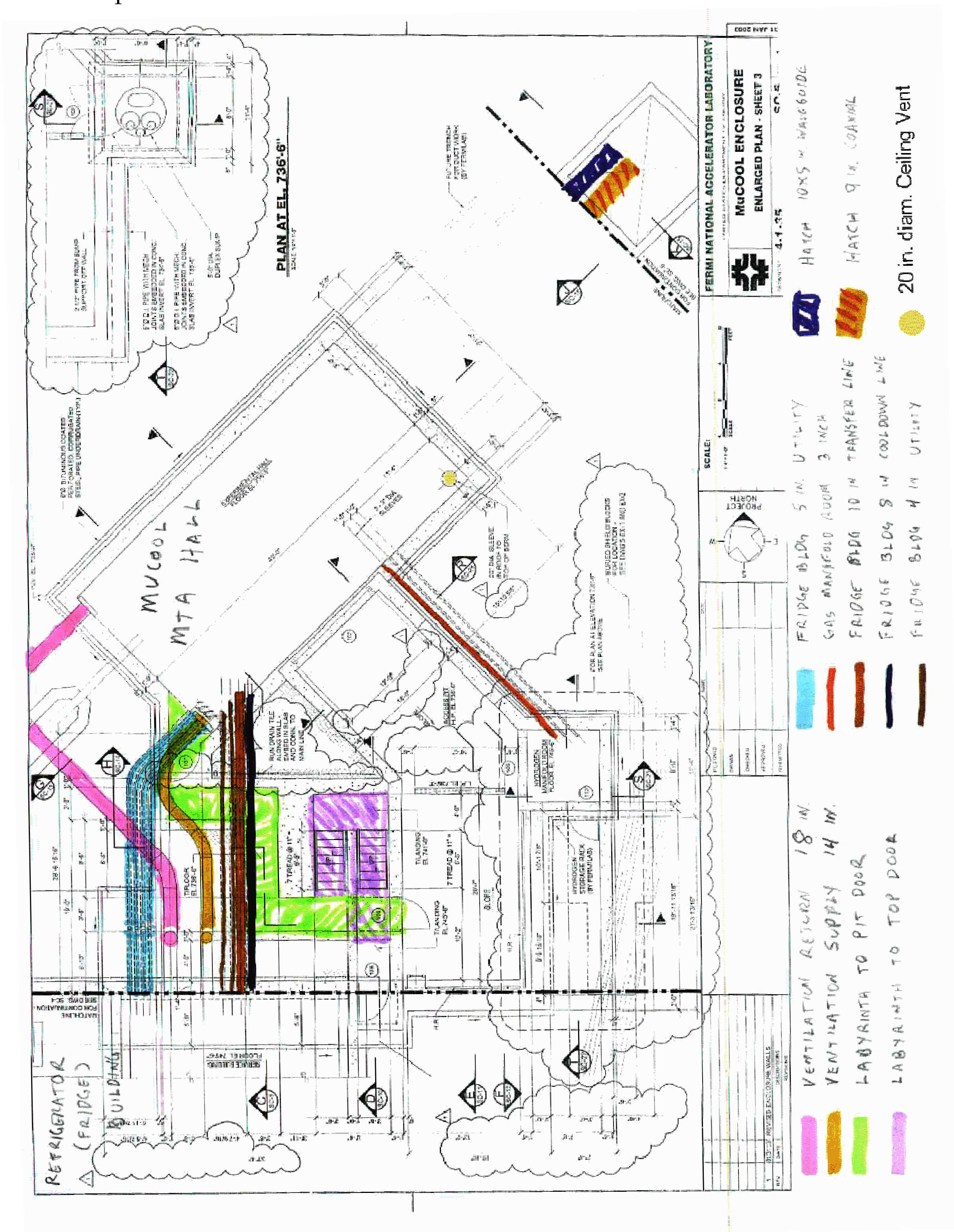

Figure 1: Map of MuCOOL Penetrations

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3 Base Dose Values for MuCOOL Penetrations

Penetrations are depicted in Figure 1.

3.1 Hatch Penetrations

Beneath the MuCOOL hatch is a concrete shield wall. This separates the MuCOOL spur in the Linac enclosure from the MTA stub and experiment hall. There are four penetrations in this shield wall:

1. 9-inch diameter coaxial transmission line
2. Rectangular waveguide, 5 x 10 inches
3. Horizontal cable tray from Linac side to MTA side, 18 x 18 inches
4. 3-inch diameter beam pipe

3.1.1 Waveguide and Transmission Line

The 5-by-10-inch waveguide and the 9-inch transmission line convey radiofrequency (RF) waves from sources in the Upper Linac Gallery through a concrete trench across the Linac berm, into the hatch, through a labyrinth in the concrete shield wall, and into MTA. They pass through labyrinths formed by hand-stacked shield blocks beneath the hatch. Sandbags are packed around them to eliminate paths for prompt radiation.

The transmission line and waveguide penetrations were simulated in MARS [2]. Beam is lost on a steel object, of 100% interaction length, placed 7 feet downstream of the shield wall. This results in a combined dose from the two penetrations of 1.15E-3 millirem per pulse, or 25.4 millirem per hour; in Reference 2 this is doubled to be conservative, resulting 2.3E-3 millirem per pulse, or 50.8 millirem per hour.

The hatch is protected by an outdoor interlocked detector.

A set of cables also passes through the trench, down the hatchway, and into a cable tray in MTA stub. Sandbags have been tightly packed around these cables so as to preclude any direct path for prompt radiation.

3.1.2 Cable Tray Penetrations and Beam Pipe

The 18-by-18-inch cable tray penetration and the 3-inch beam pipe penetration run, approximately horizontally, from the Linac side of the hatch shield wall to the MTA side.

When delivering beam to MTA, these penetrations are not a concern, because the expermiment hall is searched and interlocked before operation. However, workers may access the hall during Linac operation.

The cable tray penetration has been tightly packed with sandbags to eliminate any potential for prompt dose.

The beampipe penetration is shielded by a beamstop at the upstream end of the shield wall. Exposure during access to the MuCOOL experimental hall or beamline stub from losses in the Linac has been calculated using MARS to be less than 0.01 mrem/pulse, or, at the safety envelope rate of 22125 pulses per hour, 221 mrem/hour [5]. The area on the MTA side of the wall is protected by an interlocked detector during access to the experimental enclosure.

3.2 Gas manifold

Three penetrations of 3-inch diameter run from the MTA hall, upstream of the rollup door, to the gas manifold room above. These are single-leg straight penetrations 29.3 feet in length. They contain copper lines, of 0.25-inch diameter, to convey gases from the manifold room to MTA. They also convey some cables.

According to a MARS calculation, if these three penetrations were empty the sum of their dose rate would be no larger than 8.4E-2 millirem per pulse in each penetration, for a total not exceeding 0.25 millirem per pulse, or 5.58E3 millirem per hour. [2]

The dose has been mitigated by filling the penetrations around the copper lines with polyethylene beads. Because the copper gas lines are thin and somewhat flexible, over a 29-foot distance they sag by an amount larger than their own diameter. Thus they do not offer a straight unobstructed path to neutrons ascending the penetration. A MARS simulation, treating the penetrations as filled with polyethylene, finds the dose in the gas manifold room to be below 1.51E-3 millirem per pulse or 33.5 millirem per hour.

3.3 Ceiling Vent

The roof of the MTA hall features a vertical cylindrical penetration of 20-inch diameter. Several lines pass through it, including a 2-inch and a 3-inch line used

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for relief of the cryogenic solenoid magnet, two 1-inch lines (not presently in use), and a hydrogen recovery vacuum line of approximately 8.5 inch outer diameter. The latter leads to a vacuum tank at the bottom of the berm. It also is not presently in use, but may be employed if any future experiments use liquid hydrogen.

The 20-inch penetration is about 10.3 feet above the elevation of the beamline. Its mouth is about 11.5 feet to the side of the beam axis.

This penetration is surrounded by a hydrogen safety fence. It also lies within a larger fenced area encompassing the Linac and MuCOOL berms, which is locked and posted during operation of beam in the MTA enclosure.

For an accidental loss on an object positioned and sized to create the maximum dose, a MARS calculation estimates the dose of the empty penetration to be 1.5 millirem per pulse, or 3.32E4 millirem per hour [4].

To reduce these rates, the void between lines passing through this penetration are filled with polyethylene beads. Thus filled, a MARS calculation estimates 0.3 millirem per pulse, or 8840 millirem per hour, from the largest 8.5 inch penetration, with negligible contributions from the smaller lines.

In addition to accident doses, the dose in this ceiling vent due to normal operation is of interest. According to Reference 2, this does does not exceed 0.1 millirem per pulse, and since normal operation in Emittance Mode is up to 600 pulses per hour, the dose would not exceed 60 milliremper hour.

3.4 **Stairway Labyrinth**

The MTA personnel labyrinth has two exits, the lower one opening into the pit outside the rollup door, and the upper one leading into the parking lot beside the service building.

According to a labyrinth calculation, the dose at the lower door, treated as a 4-leg labyrinth with width 3 feet 8 inches and height 7 feet 6 inches, is 5.0E-4 millirem per pulse, or 11 millirem per hour.

The upper door is treated as a 7-leg labyrinth, neglecting vertical rise (as has been the method in previous shielding assessments). In a labyrinth calculation, the dose at this exit becomes 1.1E-7 millirem per pulse, or 2.4E-3 millirem per hour.

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3.5 Refrigerator room straight penetrations

3.5.1 Description of penetrations

Six straight single-leg penetrations run from the MTA hall, high above the floor, into the refrigerator room of the MuCOOL service building (Figure 2).

1. 10-inch-diameter penetration: This contains a 6.5-inch diameter cryogenic transfer line.

2. 8-inch penetration: This penetration contains a 4-inch diameter cooldown line.

3. Four 4-inch penetrations: Various cables and pipes run through these.

The largest penetration was simulated in detail. Doses for the smaller penetrations were derived from this simulation.

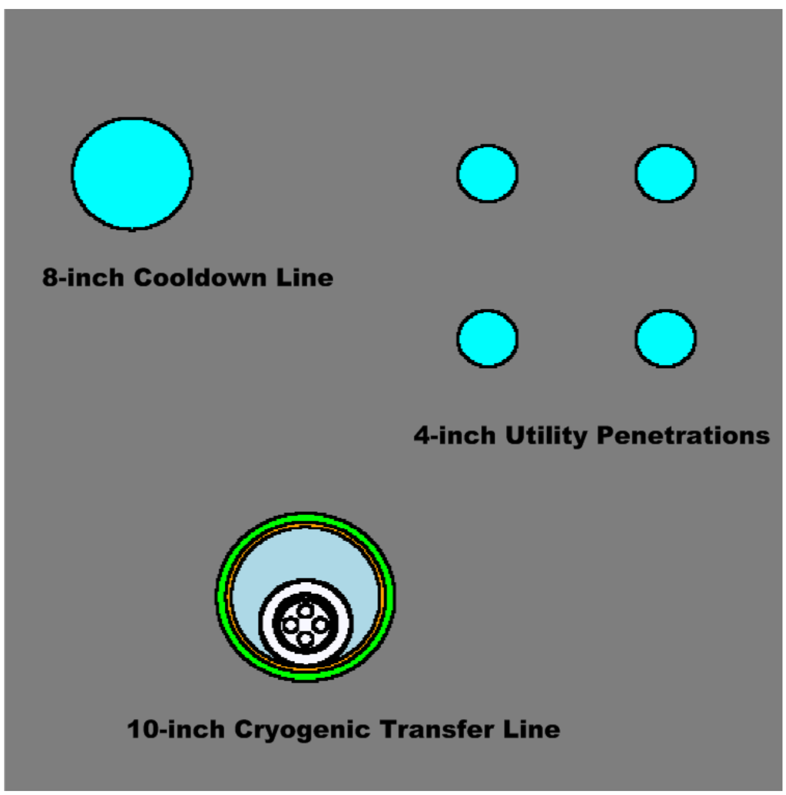

Figure 2: Layout of some refrigerator room penetrations, from TM-2457, Ref. 2.

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3.5.2 **Using 10-inch Transfer Line Penetration As an Example**

A MARS calculation was performed for the largest penetration, incorporating detailed transfer line structure, with the annulus outside the transfer line packed with polyethylene beads.

For an accident depositing beam on a 30-cm-long copper target in the worst location along the beamline within the MTA hall, the dose at the entrance to the penetration is 53 millirem per pulse. The attenuation through the transfer line is about 7E-4, giving a dose at the exit in the refrigerator room of about 3.7E-2 millirem per pulse.

To reduce doses further, a concrete wall 2 feet thick in the refrigerator room attenuates the tightly-collimated radiation. This wall shadows the exits of all six single-leg penetrations, and fencing surrounds the sides and top of this shield. No access is permitted within this enclosed volume when beam is running.

The maximum dose at accessible points outside this fence is 6E-4 millirem per pulse, at the top of the wall. [2]

3.5.3 **Extending Calculation to Smaller Refrigerator Room Penetrations**

Given the dose MARS calculates due to the transfer line penetration, the dose emerging from the five smaller single-leg penetrations may be found. We assume that dose scales with cross-sectional area, and that the maximum dose in accessible areas within the refrigerator room will be at the fenced volume enclosing the exits of these penetrations.

The single 8-inch penetration contains a 4-inch cooldown line. The annulus is packed with polyethylene shielding, so the penetration is treated as an empty 4-inch pipe. This is about 0.37 of the area of the transfer line, leading to an estimated dose of 2.27E-4 millrem per pulse.

The four 4-inch utility penetrations are partly filled with cables. Estimating conservatively, one is nearly empty, except for pipes; two are about 25% full, and one is about 50% full. Thus, about 25% of the total area of these four penetrations is blocked by cables consisting mostly of copper and plastic. Together, the four penetrations contribute 6.82E-4 millrem per pulse.

We add these together because the exits of the penetrations are in close proximity, where multiple penetrations might contribute to a worker's exposure. Dose from all six single-leg penetrations combined totals 1.51E-3 millrem per

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pulse, or 34.0 millirem per hour.

3.6 Refrigerator room 5-inch multi-leg utility penetrations

Eight utility penetrations of 5-inch diameter run from the downstream wall of MTA to the refrigerator room. They can be treated as 4-leg labyrinths, with their minimum source-to-mouth distance being 3 feet and an off-axis distance of 7 feet.

The location on the downstream wall means that losses produced at forward angles may enter these penetrations. An angle-dependent correction to the source term takes into account the higher dose rates in such cases. This is the Sullivan correction factor described in Reference 1. The smallest forward production angle possible is for a loss at the upstream shield wall, where the beam enters the enclosure. This angle, 6.16 degrees, corresponds to a loss 70 feet upstream; at any other loss location, production angles would be larger.

To set a conservative upper limit on dose rates, a labyrinth calculation employed the shortest possible source-to-mouth distance and off-axis distance (which would entail a loss close to the downstream wall, and hence a large production angle) combined with the smallest possible production angle (which would entail a loss far upstream). A real loss will be smaller than the value calculated from these pessimistic assumptions.

The dose rate thus estimated for a single penetration is about 4.9E-16 millirem per pulse or 1.1E-11 millrem per hour, so the combined dose from all would not exceed 3.92e-15 millirem per pulse, or 8.7E-11 millirem per hour.

3.7 Ventilation ducts

Two ventilation ducts serve MTA. The supply duct is treated as a 4-leg labyrinth 14.3 inches in diameter. Again its mouth is in the downstream wall, so it is treated in the same manner as the refrigerator room utility penetrations described above, with source-to-mouth distance of 8 feet, off-axis distance of 11.5 feet, and minimum forward angle 11.38 degrees.

Dose at the supply duct exit is 9.32E-10 millirem per pulse, or 2.1E-5 millirem per hour, on the roof of the service building.

The return duct, treated as a 4-leg labyrinth 18.1 inches in diameter, is also in the

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downstream wall. It has source-to-mouth distance of 8 feet, off-axis distance of 6.8 feet, and minimum forward angle 8.5 degrees.

Dose at the return duct exit is 2.97E-9 millirem per pulse, or 6.6E-5 millirem per hour, on the roof of the service building.

4 2010 Shielding Assessment Beam Conditions

The 2010 MuCOOL Facility Shielding Assessment [1] considers two types of operating conditions: Emittance Mode, where beam normally terminates in the emittance absorber in the MTA stub, and Experiment Mode, where beam normally terminates in an experimental apparatus or in the final beam absorber downstream of MTA.

Doses given under Base Dose conditions above may be scaled to beam conditions for these two modes.

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4.1 Emittance Mode

4.1.1 Accident Conditions

Accidental doses from Emittance Mode operation may be scaled from the results obtained for base dose conditions, as described in Section 2.2 above.

In Emittance Mode, 600 pulses per hour of 400 MeV protons are delivered with an intensity of 1.6E13 protons per pulse (9.8E15 protons per hour).

For the penetrations in MTA, doses are approximated by the values due to beam lost in the worst-case locations for each penetration. In reality such losses would occur upstream of the emittance absorber, a region which is not the worst-case location for most of the penetrations. This approximation is therefore conservative.

Under this assumption, an upper limit on accident dose rates is given in Table 1.

Table 1: Emittance Mode Accident Doses

Location	Base Dose mrem/pulse	Emittance Mode Accident Dose mrem/pulse	Emittance Mode Accident Dose mrem/hour
Hatch 9 in Coaxial	2.30E-03	2.30E-03	1.38E+00
Hatch 5x10 in Waveguide	2.30E-03	2.30E-03	1.38E+00
20 in Ceiling Vent	3.00E-01	3.00E-01	1.80E+02
3 Gas Manifold Room 3 in.	1.51E-03	1.51E-03	9.06E-01
8 in Cooldown Line	2.27E-04	2.27E-04	1.37E-01
10 in. Transfer Line	6.00E-04	6.00E-04	3.60E-01
4 x 4 in Fridge Room	6.82E-04	6.82E-04	4.10E-01
Sum of Fridge Room Pens	1.51E-03	1.51E-03	9.06E-01
MTA Labyrinth Pit Door	5.02E-04	5.02E-04	3.01E-01
MTA Labyrinth Top Door	1.10E-07	1.10E-07	6.60E-05
8 x 5 in Utility Fridge Room	3.92E-15	3.92E-15	2.35E-12
MTA Ventilation Supply	9.32E-10	9.32E-10	5.59E-07
MTA Ventilation Return	2.97E-09	2.97E-09	1.78E-06

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4.1.2 Normal Operation

In normal operation, Emittance Mode beam will be stopped in the emittance absorber up to 600 times per hour. In general, doses due to such operation will not exceed accidental doses given above, so the accdental dose values are used conservatively to approximate normal-operation doses.

In particular, the ceiling vent dose has been simulated, as discussed in section 3.3 above.

4.2 Experiment Mode

4.2.1 Accident Conditions

In Experiment Mode, 60 pulses per hour of 400 MeV particles are delivered with an intensity of 1.6E13 protons per pulse (9.8E14 protons per hour).

An upper limit on accident dose rates in Experiment Mode, for the penetrations in MTA, is given in Table 2. As in the case of the Emittance Mode, doses are approximated by the values due to beam lost in the worst possible locations, on a target that maximizes dose, for each penetration.

Table 2: Experiment Mode Accident Doses

Location	Base Dose mrem/pulse	Experiment Mode Accident Dose mrem/pulse	Experiment Mode Accident Dose mrem/hour
Hatch 9 in Coaxial	2.30E-03	2.30E-03	1.38E-01
Hatch 5x10 in Waveguide	2.30E-03	2.30E-03	1.38E-01
20 in Ceiling Vent	3.00E-01	3.00E-01	1.80E+01
3 Gas Manifold Room 3 in.	1.51E-03	1.51E-03	9.06E-02
8 in Cooldown Line	2.27E-04	2.27E-04	1.37E-02
10 in. Transfer Line	6.00E-04	6.00E-04	3.60E-02
4 x 4 in Fridge Room	6.82E-04	6.82E-04	4.10E-02
Sum of Fridge Room Pens	1.51E-03	1.51E-03	4.53E-02
MTA Labyrinth Pit Door	5.02E-04	5.02E-04	3.01E-02
MTA Labyrinth Top Door	1.10E-07	1.10E-07	6.60E-06
8 x 5 in Utility Fridge Room	3.92E-15	3.92E-15	2.35E-13
MTA Ventilation Supply	9.32E-10	9.32E-10	5.59E-08

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MTA Ventilation Return	2.97E-09	2.97E-09	1.78E-07

4.2.2 **Normal Operation**

Doses due to normal operation of an experiment will depend strongly upon the configuration of the experimental apparatus. They must be determined on a case-by-case basis, and approved by the Radiation Safety Officer, and will not be considered here.

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5 References

1. Carol Johnstone et al, "MuCOOL Facility Shielding Assessment," June 2010.

2. Igor Rakhno and Carol Johstone, "Beam Accident Scenarios for MuCOOL Test Area," TM-2457, Fermilab, June 2010.

3. Kamran Vaziri, "Dose Attenuation Methodology for NuMI Labyrinth, Penetrations and Tunnels," Radiation Protection (RP) Note 140, Fermilab, May 2003.

4. Igor Rakhno, personal communication, 15 April 2009, and file "H2_vent_stack.ppt" at <http://www-ap.fnal.gov/users/rakhno/MuCool/MTA/2009/H2_vent_stack.ppt>, retrieved 16 April 2009.

5. As cited in Reference 1, page 8, dose due to beam pipe penetration through the shield wall was simulated by Igor Rakhno.

6 Appendices

1. Mucool Labyrinths and Penetrations Assessment Summary, Emittance Mode

2. Mucool Labyrinths and Penetrations Assessment Summary, Experiment Mode

Worksheets from workbook "Labyrinth Calculations Mucool Penetrations.xls:"

3. Mucool Stairway Labyrinth Pit Door

4. Mucool Stairway Labyrinth Top Stairway Door

5. Mucool Ventilation Supply Penetration

6. Mucool 18-inch Ventilation Return Penetration

7. Mucool 5-inch Utility Penetrations